Efficient Model Checking with Semantically-Equivalent Models for *vGOAL*

Extended Abstract

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ABSTRACT

Model checking offers a powerful approach to ensuring safety and reliability in autonomous systems. However, existing model-checking approaches for agent programming languages (APLs) face challenges in equivalent semantic mapping, efficient model generation, and integration with high-performance model checkers. We present a computation tree logic (CTL) model-checking framework for *vGOAL*, where both the interpreter and model-checking framework share the same state update implementations. Our framework establishes semantically equivalent models of *vGOAL* programs, implements efficient state space generation, and integrates with the NuSMV model checker. Through a case study of an autonomous logistic system with up to three robots, we demonstrate significant improvements in model-checking efficiency, enabling verification of complex autonomous systems.

KEYWORDS

CTL Model Checking,*vGOAL*, Autonomous Decision-Making

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1 INTRODUCTION

As autonomous systems become more prevalent, APLs like AgentSpeak [5], Gwendolen [11], and GOAL [17] have emerged as essential tools for programming autonomous decisions. These languages are designed to model autonomous decision-making by enabling agents to perceive their environment and make decisions based on rules. Formal verification through model checking offers a promising approach to ensure their reliability [22, 25], and numerous efforts have been dedicated to model checking agent programs [2–4, 8, 12–14, 16, 18, 21, 24, 26, 29]. Existing methods face significant challenges in semantic equivalence, model generation efficiency, and scalability [3, 15, 16, 21].

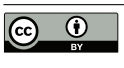
Modern advancements in model checkers enable handling state spaces with hundreds of millions of states [1, 6, 7, 9, 19], making them suitable for verifying complex autonomous systems. However, applying these to APLs involves difficulties such as semantically-equivalent model generation, inefficiency of interpreters, and limited scalability for multi-agent settings. Current interpreter-based frameworks like MCAPL [10] and IMC [20, 21] have been applied to languages such as Gwendolen, GOAL, and AgentSpeak [18] but show limitations like inefficiency [16]. Alternative non-interpreter-based methods [3] suffer from complicated semantic mapping from agent programs to the input format for a model checker, like Promela [23]. Our recent work [27, 29] ensures semantic equivalence for GOAL programs but is constrained to single-agent systems.

To address these challenges, we develop a CTL model-checking framework for *vGOAL* [28], a variant of GOAL designed for verifiable autonomous decision-making. Our framework makes three key contributions: (1) establishing semantically-equivalent models for *vGOAL* programs, (2) developing an efficient state space generation algorithm, and (3) integrating NuSMV for efficient CTL model-checking. To demonstrate the practical application and scalability of our framework, we conduct a case study involving a logistics transportation system with multiple autonomous robots. The results demonstrate substantial improvements in verification efficiency and scalability, establishing a foundation for model-checking complex multi-agent autonomous systems programmed in *vGOAL*.

2 CTL MODEL-CHECKING FRAMEWORK

The CTL model-checking framework for *vGOAL* is designed to enable the efficient verification of the semantically-equivalent models of *vGOAL* programs. The *vGOAL* model-checking framework is an interpreter-based model-checking framework, and it shares the same state update implementationits with its interpreter [30], enabling semantically-equivalent model generation. As illustrated in Figure 1, the framework consists of three components: non-deterministic modeling, NuSMV encoding, and NuSMV verification. Our primary focus is on the first two components—non-deterministic modeling and NuSMV encoding. Non-deterministic modeling encompasses both the generation of semantically-equivalent models and the implementation of efficient model generation techniques.

Non-Deterministic Modeling. The semantically-equivalent model generation begins by constructing a transition system from a given *vGOAL* program. The transition system captures all possible states, transitions, and terminal states of the program. Each state is iteratively expanded to explore all agent transitions, with terminal states identified when agents have completed their goals. By sharing state update implementations with the *vGOAL* interpreter, the framework ensures the generated model accurately reflects the



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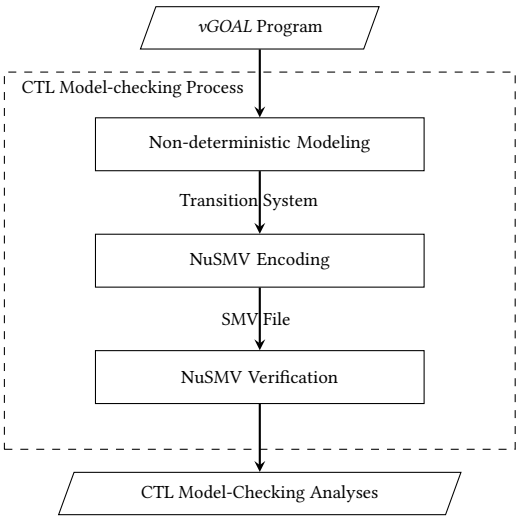

Figure 1: The Overview of CTL Model-Checking Framework for *vGOAL*.

exact execution behavior of the original program. This equivalence can be formally established through the existence of a bisimulation relation between the transition system and all possible executions of the *vGOAL* program. Additionally, atomic proposition labeling is employed to represent properties based on state attributes.

To enhance efficiency, optimizations are applied during state exploration. A caching mechanism prevents redundant computation for revisited states, and deterministic updates efficiently handle instances where agents switch focus between goals. Both techniques contribute to significant computational savings without compromising semantic correctness. An example of a generated transition system illustrates the iterative state expansion and the way agent transitions are modeled, showcasing the straightforward representation of non-deterministic agent behaviors. The framework implements an optimization for state exploration in the form of an improved expansion function. This function incorporates a caching mechanism to store previously computed transitions, significantly reducing redundant computations when states are revisited. For scenarios in which agents dynamically switch focus between goals, the approach efficiently updates transitions to reflect the altered goal prioritization. The improved function produces a transition system that is identical to the one generated by the original method, ensuring full correctness while delivering better computational efficiency.

NuSMV Encoding. Once the transition system is generated, it is encoded into a NuSMV-compatible format. This encoding process begins by preprocessing the system's properties, including safety, error, and termination conditions defined in the *vGOAL* program. These properties are classified and mapped to the states of the transition system. The encoding process converts each component of the transition system—states, transitions, terminal states, atomic propositions, and associated properties—into their respective representations in an SMV file. This automated encoding includes CTL properties for safety (to ensure that no undesirable states are reached) and liveness (to check the existence of paths leading to terminal states). For example, for a transition system representing agent behaviors, the encoding might specify that the agent is always in a safe or valid state and check the existence of error-free paths to a terminal state. These CTL properties enable NuSMV to validate the program's correctness and reliability, ensuring the autonomous system behaves as designed.

NuSMV Verification. NuSMV takes the encoded SMV file as input and automatically performs the CTL model-checking analysis, and it produces the CTL model-checking analysis as the output, indicating whether the specified CTL properties are satisfied or not. These results are crucial for validating the reliability and correctness of the *vGOAL* program, ensuring that the autonomous system behaves as intended.

3 EMPIRICAL ANALYSES

We evaluated our CTL model-checking framework through a case study of an autonomous logistics system, comparing the original framework against the improved version that incorporates efficient model generation algorithms. The experiments were performed under three configurations involving one, two, and three agents, each capable of managing multiple delivery goals.

Our analysis revealed that both the number of goals and agents correlate positively with the state space size, with agent count having a more significant impact. Notably, the state space converges to a finite value regardless of further increases in goals or agents. The improved framework consistently outperforms the original version across all test scenarios, with modeling time dominating the overall execution time in both versions.

The performance gap between the two versions becomes more significant as system complexity increases. This superior performance stems from reducing the time complexity from $O(goals \times states)$ to $O(states)$. This optimization proves particularly valuable for complex scenarios involving multiple goals and agents, where the original framework's performance degrades significantly.

4 CONCLUSIONS AND FUTURE WORK

This paper presents a comprehensive CTL model-checking framework for *vGOAL* that effectively addresses three major challenges in APL model-checking: semantically-equivalent mapping, efficient model generation, and integration with efficient model checkers. Through empirical analysis of 30 scenarios, we demonstrate that our efficient model generation algorithm significantly reduces time complexity while efficiently verifying complex autonomous systems, with the notable observation that state space converges to a constant number as goals increase. Future work will explore the theoretical underpinnings of state space convergence in *vGOAL* programs, aiming to simplify model generation by identifying the point of convergence and enhancing the verification of multi-goal autonomous systems.

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